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ELECTROMAGNETIC MEASUREMENTS

A METHOD OF EXTENDING THE DYNAMIC RANGE WHEN TRANSFERRING THE DIMENSIONS OF THE UNIT OF ELECTROSTATIC FIELD STRENGTH

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Two equivalent methods of extending the dynamic range when transferring the dimensions of the unit of electrostatic field strength are proposed and analyzed. Both methods are based on the fact that the electrostatic field strength depends on the parameters of the electrostatic field generator and the position of the point of observation.

Key words: *electrostatic field, generator, dynamic range.*

The instruments for measuring the strength of a constant electric (electrostatic) field in free space (for example, the ÉSPI-301 and the ST-01), employed to monitor the requirements on electromagnetic safety, have an electric field strength measurement range of 0.3–180 kV/m. Such measuring instruments are checked by a direct measurement using working standards of the second class (the type RÉNÉP-00), where the range of reproduction of the electric field strength is 0.1–200 kV/m. According to the checking scheme [1], an RÉ2 check should be carried out using a working standard of the first class or the GÉT 158-96 State Standard by a comparison method. In this case, one uses as the comparator the standard instrument for measuring electric field strength, described in the GÉT 158-96 standard. However, in the working standard of the first class and in the GÉT 158-96, the electric field strength is reproduced in the range 0.01–2 kV/m, and hence, strictly speaking, the comparison method when checking the working standard can only be used in this range. In the range 2–200 kV/m, the working standard of the second class is checked using a standard measuring instrument by direct measurements. Clearly, the requirements imposed on the metrological characteristics of this measuring instrument differ considerably for comparisons and direct measurements of electric field strength.

In the first case, one mainly requires that the characteristics of the standard measuring instruments (SMI) should be stable and should have a small root mean square deviation of the random error. In the second case, it is necessary that the limit of the permissible error in measuring electric field strength should be of the same order as the permissible error in reproducing electric field strength in a working standard of the 1st class. Here, the standard measuring instrument actually acts as a working standard of the 1st class and is used to transfer the dimensions of the unit of electric field strength to a working standard of the 2nd class by the direct measurement method.

In order to be able to use a standard measuring instrument to transfer the dimensions of the unit by the direct measurement method, one must calibrate the standard measuring instrument in the range 2–200 kV/m, i.e., one must obtain the calibration coefficient k, which occurs in the measurement formula

$$E = kE^{\mathrm{SMI}},$$

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TABLE 1. Calibration Points of the Standard Measuring Instrument (SMI)

$E_{\lim}^{SMI}$, kV/m	E_i^s, kV/m	k_i
0.2	0.100	k_1
	0.150	k_2
2.0	0.25	k_3
	0.5	k_4
	1.0	k_5
	1.5	k_6
20	2.5	k_7
	5	k_8
	10	k_9
	15	k_{10}
200	25	k_{11}
	50	k_{12}
	100	k_{13}
	150	k_{14}

from which one calculates the measured value of the electric field strength E from the readings E^{SMI} of the standard measuring instrument.

The calibration coefficient k depends on the measured electric field strength E. Hence, it must be determined for different values of E over the whole range of measurement. Up to now, this has been done by an indirect method. From the beginning, in the State Standard GÉT 158-96 the chosen values of the standard electric field strength E_i^s were measured in the range 0.1–2 kV/m using a standard measuring instrument (see the table), and the calibration coefficients of the standard measuring instrument were calculated from the formula

$$k_i = E_i^s / E_i^{SMI},$$

where i is the number of the measurement point.

In the table, $E_{\lim}^{SMI}$ are the limits of measurement of the standard measuring instrument.

The values of k_7, ..., k_{14} when $E_i^s > 2$ kV/m were then assumed to be equal to k_6. This step is based on the results of investigations of the linearity of the amplifier of the standard measuring instrument. This method is fairly widely used to broaden the dynamic range of instruments for measuring electric field strength, but it has not been possible to justify it rigorously and correctly estimate its error. The main reason is the fact that, when investigating the linearity of an amplifier, it is difficult to reproduce the conditions under which the amplifier operates into an antenna when measuring electric field strength.

Description of the Calibration of the Standard Measuring Instrument. The basic principle of the proposed method of extending the dynamic range (determining the calibration coefficients of the standard measuring instrument when $E^s > 2$ kV/m) is as follows. Suppose we have two standard capacitors with different distances between the plates d_1 and d_2 (Fig. 1) and a high-voltage source, which enables one to establish in capacitor *1* ($d_1 < d_2$) an electric field strength in the range 0.1–200 kV/m. We connect the capacitors in parallel with the constant voltage source, at the output of which a voltage U is established. The electric field strength at the center of capacitor *1* will then be $E_{k1} = \alpha_1 U / d_1$, while at the center of capacitor *2* it will be $E_{k2} = \alpha_2 U / d_2$, where α_1 and α_2 are coefficients which take into account the finite dimensions of the capacitor plates and depend on the ratio of the radius of the plates to the distance between them. For infinite plates, $\alpha_1 = \alpha_2 = 1$.

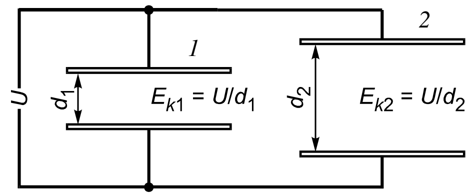

Fig. 1. Calibration of the standard measuring instrument by the two-capacitor method.

If the radius of the capacitor plates is much greater than the distances between them, we will have $\alpha_1 \approx \alpha_2 \approx 1$ provided that the point of observation is situated at the center of the capacitor. Consequently, E_{k1} and E_{k2} are connected by the relation

$$E_{k1}/E_{k2} = \alpha_1 d_2/\alpha_2 d_1 = k,$$

from which it follows that

$$E_{k1} = kE_{k2}. \tag{1}$$

We will assume that the distances d_1 and d_2 can be measured fairly accurately, while the ratio of the radius of the plates to the distance between them for capacitors *1* and *2* is the same and, consequently, $\alpha_1 = \alpha_2$. Hence, the coefficient k can be assumed to be known. Note that the coefficient k is independent of the electric field strength. Suppose further that the standard measuring instrument is calibrated as described in GÉT 158-96 in the 0.1–2 kV/m range, i.e., according to the table the calibration coefficients k_1–k_6 are known. We place the antenna of the standard measuring instrument at the center of capacitor *2*, and using the standard measuring instrument we establish in capacitor *2* an electric field strength, for example, $E_{k2} = 0.25$ kV/m. To do this, we must apply to capacitors *1* and *2* a voltage U such that the readings of the measuring instrument $E_{k2}^{\mathrm{SMI}} = E_{k2}/k_3$. Then, by (1), the electric field strength in capacitor *1* will be $E_{k1} = kE_{k2}$. We will assume that the distances d_1 and d_2 have been chosen so that $k = 10$. Then, an electric field strength $E_{k1} = 2.5$ kV/m will be established in capacitor *1*. We place the antenna of the standard measuring instrument in capacitor *1* and record the readings E_{k1}^{SMI}, corresponding to the measured electric field strength $E_{k1} = 2.5$ kV/m. We can then obtain the calibration coefficient k_7 of the standard measuring instrument for the electric field strength of 2.5 kV/m, by dividing E_{k1} by E_{k1}^{SMI}. Continuing this process, we obtain all the calibration coefficients in succession.

In practice, when carrying out the above procedure we can manage with one unscreened capacitor. The point is that in the standard use of a standard measuring instrument we take the value at the center of the capacitor as the standard value of the electric field strength. If the point of observation is displaced in the plane of symmetry of the capacitor (the plane passing through the center of the capacitor and parallel to its plates, Fig. 2), the electric field strength will decrease with distance from the center of the capacitor.

Hence, instead of the arrangement of two capacitors and a high-voltage source described above, to calibrate the standard measuring instrument one can use a working standard of the 2nd class, but the electric field strength is measured at different points in the plane of symmetry. In particular, if one uses the RÉNÉP-00 working standard, then, for a distance from the center of its capacitor r, equal to the radius of the plates, the electric-field strength is reduced by a factor of ten, which corresponds to $\alpha_2 = 0.1\alpha_1$ when $d_2 = d_1$ in the example of two capacitors considered above.

It follows from the above that, for the electric field strength at the center of capacitor $E_i(0)$ and for the electric field strength at a distance r from the center of the capacitor, we have the formulas

$$E_i(0) = k_i E_i^{\mathrm{SMI}}; \quad E_i(r) = k_{i-4} E_{i-4}^{\mathrm{SMI}}. \tag{2}$$

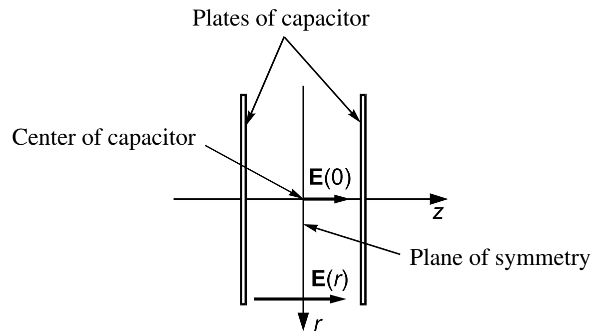

Fig. 2. Calibration of the standard measuring instrument in a single capacitor.

According to the table, the subscript i defines the nominal value of the electric field strength established at the center of the capacitor of the working standard of the 2-nd class (the order number of the value of the electric field strength in the table). Since $E_i(r)/E_i(0) \approx 0.1$, this means that for the same value of the electric field strength established at the center of the capacitor, when measuring $E_i(r)$ the readings of the standard instrument will be one tenth of its readings when measuring $E_i(0)$. Consequently, when measuring $E_i(r)$ after measuring $E_i(0)$ it is necessary to transfer to the previous limit of measurements of the standard measuring instrument, which corresponds to reducing i by four units. This is also reflected in formula (2).

Using them, we can express k_i in terms of k_{i-4}:

$$k_i = \frac{E_i(0) E_{i-4}^{\mathrm{SMI}}}{E_i(r) E_i^{\mathrm{SMI}}} k_{i-4}. \tag{3}$$

We will introduce the attenuation factor of the electric field strength in the capacitor of the working standard of the 2nd class:

$$k_e = E_i(r) / E_i(0).$$

By definition, k_e is independent of the number i, since it is a characteristic of a standard capacitor and depends only on its dimensions and the distance r. Hence, k_e can be calculated or obtained experimentally. For example, we can put

$$k_e = \frac{E_6(r)}{E_6(0)} = \frac{k_2 E_2^{\mathrm{SMI}}}{k_6 E_6^{\mathrm{SMI}}}.$$

We will rewrite (3), using k_e:

$$k_i = \frac{1}{k_e} \frac{E_{i-4}^{\mathrm{SMI}}}{E_i^{\mathrm{SMI}}} k_{i-4}. \tag{4}$$

This is also the required measurement formula for determining k_i. It enables one to find all the calibration coefficients of the standard measuring instrument in succession, if we know at least one of the limits. In the limits of measurements of 0.2 kV/m and 2 kV/m, the calibration coefficients from k_1 to k_6 are given in the State Standard. According to (4), from the results of measurements of the electric field strength in the working standard at the center of the capacitor and at a distance r from the center, for the same voltage on the capacitor, we can find the calibration coefficients at the limit of measurements of 20 kV/m (from the k_7 to k_{10}), and then in a similar way we can find the calibration coefficients at the limit of 200 kV/m.

Conclusions. We have proposed and analyzed in detail two equivalent methods of extending the dynamic range when transferring the unit of measurement of electrostatic field strength, based on the fact that the field strength depends on the parameters of the generator and on the position of the point of observation at which its strength is measured. Both methods can, in principle, also be used in the case of an alternating electric field.

REFERENCE

1. State Standard GOST R 8.564-96, GSI, *The State Checking Scheme for Measuring Electric Field Strength in the 0–20 kHz Range*.